WET ACID DEPOSITION EFFECTS ON SOIL PROPERTIES IN RELATION TO FOREST GROWTH. EXPERIMENTAL RESULTS.

Abrahamsen, G. 1), Tveite, B. 2), and Stuanes, A.O.2)

1) Institute of Soil Sciences, Agricultural University of Norway,
N-1432 Aas-NLH, Norway,
2) Norwegian Forest Research Institute, N-1432 Aas-NLH, Norway.

ABSTRACT

Field plots, 75 m^2 in size, were supplied with 50 mm of artificial rain 38 times from 1974 to 1981. "Rain" of varying acidities was produced using groundwater mixed with sulphuric acid. The experiment was carried out in a homogeneous stand of Scots pine planted in 1968-70 on an Orthic Humo-Ferric Podzol.

Tree growth and soil properties have been significantly influenced by application of "rain" of pH 3 and below. From 1974 to 1977 these treatments gave rise to increased growth, but later the growth decreased significantly. In 1986 indications of improved growth were observed. Both pH and base saturation decreased during the first 4 to 7 years of the experimental period, but stabilized or increased slightly in the succeeding period.

The growth effects seem to be caused by an increased availability of N in the first period and a reduced supply of Mg in the following period. Increased mobilization of Al can hardly explain the reduced growth.

KEY WORDS
Acid precipitation, aluminium, base saturation, Scots pine, soil pH, tree growth.

INTRODUCTION

Atmospheric pollution in Norway originates mainly from remote sources in the densely populated and industrialized areas of Central Europe. Because of the long distance from the main emission sources wet deposition dominates over dry deposition. In general wet deposition in Norway is considered to represent about 75 per cent of the total deposition of both sulphur and nitrogen (Overrein et al., 1980).

Because of the importance of wet deposition in relation to dry deposition the research on effects of pollutants has concentrated on wet deposition. The main emphasis has been placed on experimental research. From 1972 to 1975, five field experiments were established in Norwegian forests to examine the effects of artificially acidified rain on soil properties, growth and nutrient status of trees. This paper describes the results from one such experiment on Scots pine (Pinus sylvestris L.). Preliminary results from this experiment have been published by Abrahamsen et al. (1976a), Stuanes (1980), Tveite (1980a and b), Tveite and Abrahamsen (1980), Abrahamsen et al. (1983), and Abrahamsen (1984).

MATERIALS AND METHODS.

The experiment was established at Åmli (8°32'E, 58°49'N), on a flat plain of deep glacifluvial deposits above Precambrian and Permian crystalline bedrock. The mineral material (< 2mm) in the E- and Bs-horizons consists of 1 per cent clay, 28 per cent silt and 71 per cent sand. In the C-horizon the contents of clay, silt and sand are 0.5 per cent, 0.5 per cent and 99 per cent respectively. The amount of gravel and stones increases from about 20 per cent in the E-horizon to about 30 per cent in the upper part of the C-horizon. The soil is an Orthic Humo-Ferric Podzol. The pH(H_2O) in the organic horizon varies between 3.7 and 4.1, increasing to about 4.7 to 5.1 in the C-horizon.

The area is stocked with Scots pine (Pinus sylvestris L.) planted between 1968 and 1970. In 1974, when the trees were about 1.5 m high, 60 plots of 75 m^2 each were established. The plots were treated with artificial rain of pH from 6 to 2 in combination with lime in amounts from 0 to 4500 kg ha^{-1}. Only results from the unlimed plots are shown in the present study. Each treatment was replicated 3 times. Further description of the experiment and the soil has been given by Abrahamsen et al. (1976b) and Stuanes and Sveistrup (1979).

The artificial rain was produced from groundwater mixed with sulphuric acid to obtain the desired pH values. The applications took place from 1974 to 1981, usually five times per year in the frost-free period, altogether 38 times. The plots were not sheltered from natural precipitation. pH and lime potential of the bulk of the artificial and the natural rain are shown in Table 1 together with the total amount of SO_4-S deposited in the different treatments. The high lime potential of the pH 6 and the pH 4 treatments is due to the higher concentrations of Ca and Mg in the groundwater than in the rainwater. The table also shows the amount of precipitation with a pH of 4.2 and (Ca + Mg) = 7 uM (rain quality from one of the most polluted areas in Norway) which is equivalent to the amount of acidifying material deposited in the different treatments.

TABLE 1. pH AND LIME POTENTIAL (LP) OF BULK PRECIPITATION, THE EQUIVALENT AMOUNT OF PRECIPITATION WITH pH 4.2 AND A CONCENTRATION OFCA + MG OF 7 uM $^{b)}$, AND THE TOTAL AMOUNT OF S DEPOSITED DURING THE WATERING PERIOD.

Treatment	n.w.[a]	pH 6	pH 4	pH 3	pH 2.5	pH 2
Bulk pH	4.18	4.30	4.14	3.58	3.14	2.66
Bulk LP	1.6	1.9	1.7	1.2	0.7	0.25
Precip. (m)$^{b)}$	7.1	4.8	6.9	25.2	69.4	210.0
SO_4-S kg ha^{-1}	80	100	145	410	1250	3630

[a] not watered

Tree height and girth increment have been measured each autumn since 1974. Foliar nutrient concentrations in current and previous years' needles were measured all years except 1979. Needle samples from eight trees per plot were taken in November - December from the third branch whorl from the top of the trees. Soil samples were taken in October 1975, 1978, 1981 and 1984 from the O- and E-horizons and from two depths in the Bs-horizons. Twenty subsamples were pooled by horizon for each plot. Exchangeable cations were determined by extracting the soil with 1 M NH_4OAc at pH 7. Soil pH was measured in a 1:2.5 soil to water suspension. Further description of the analytical methods has been given by Ogner et al. (1984).

RESULTS.

Since the potential cation exchange capacity (CEC) was used, CEC has not been changed by the treatments. CEC varies between 1350 $mmol_c\ kg^{-1}$ in the O-horizon to about 20 $mmol_c\ kg^{-1}$ in the lower part of the Bs-horizon (24-29 cm soil depth). Because of the method by which CEC was measured,

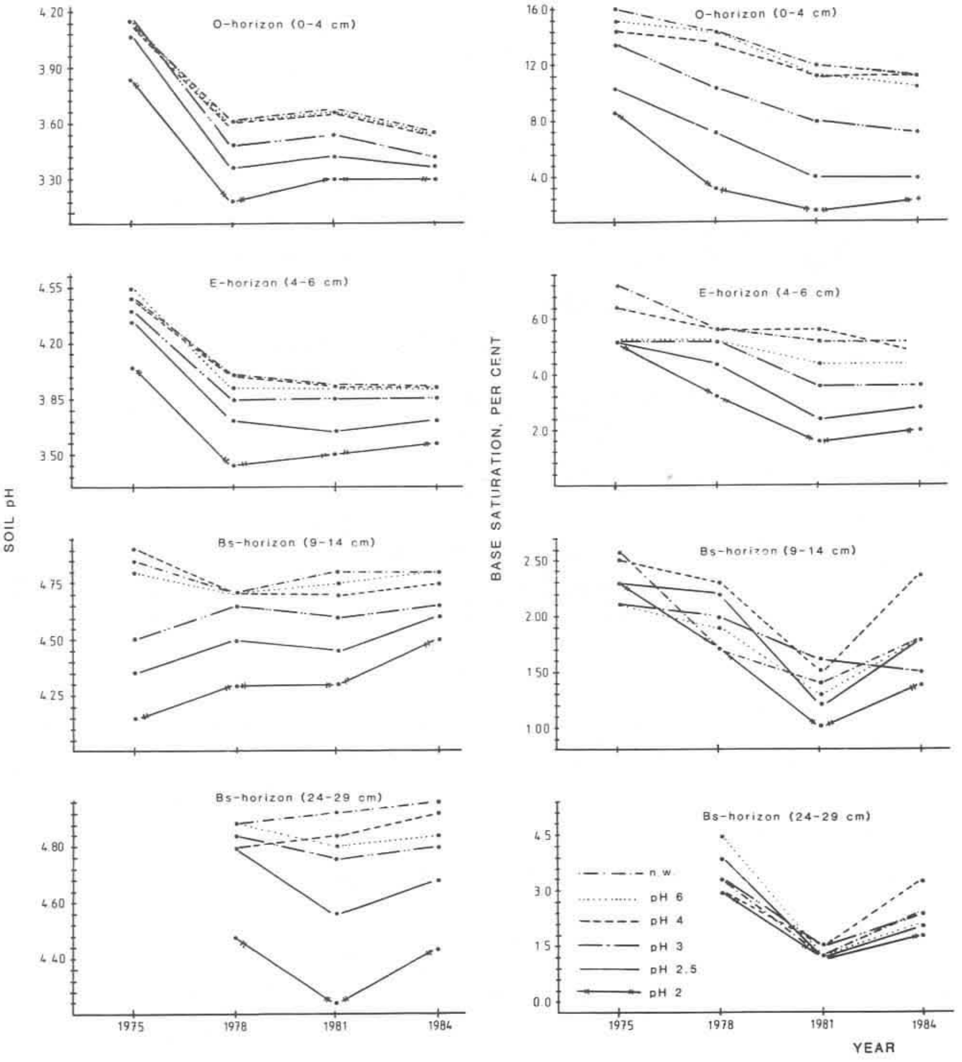

Figure 1. Effects of acid application on soil pH(H_2O) and base saturation.

the base saturation is a good measure of possible changes in the pool of exchangeable cations in the soil. Variation in the soil pH and base saturation in the different treatments is shown in Figure 1. In the O- and E-horizons soil pH decreased significantly from 1975 to 1978 in all treatments. In the upper part of the Bs-horizon (9-14 cm soil depth) the changes were much smaller, and the changes in the least acidic treatments were not consistent with those in the most acidic treatments. Samples from the lower part of the Bs-horizon were not taken in 1975. The effect of the acid application on soil pH can be seen in all soil layers. The most significant effects are found after the two most acidic treatments, but also the pH 3 treatment appears to have reduced soil pH, especially in the O- and E-horizons. From 1981 to 1984 the differences among the treatments may have been reduced. The base saturation decreased gradually from 1975 to 1984 in the O- and E-horizons in all treatments. During the

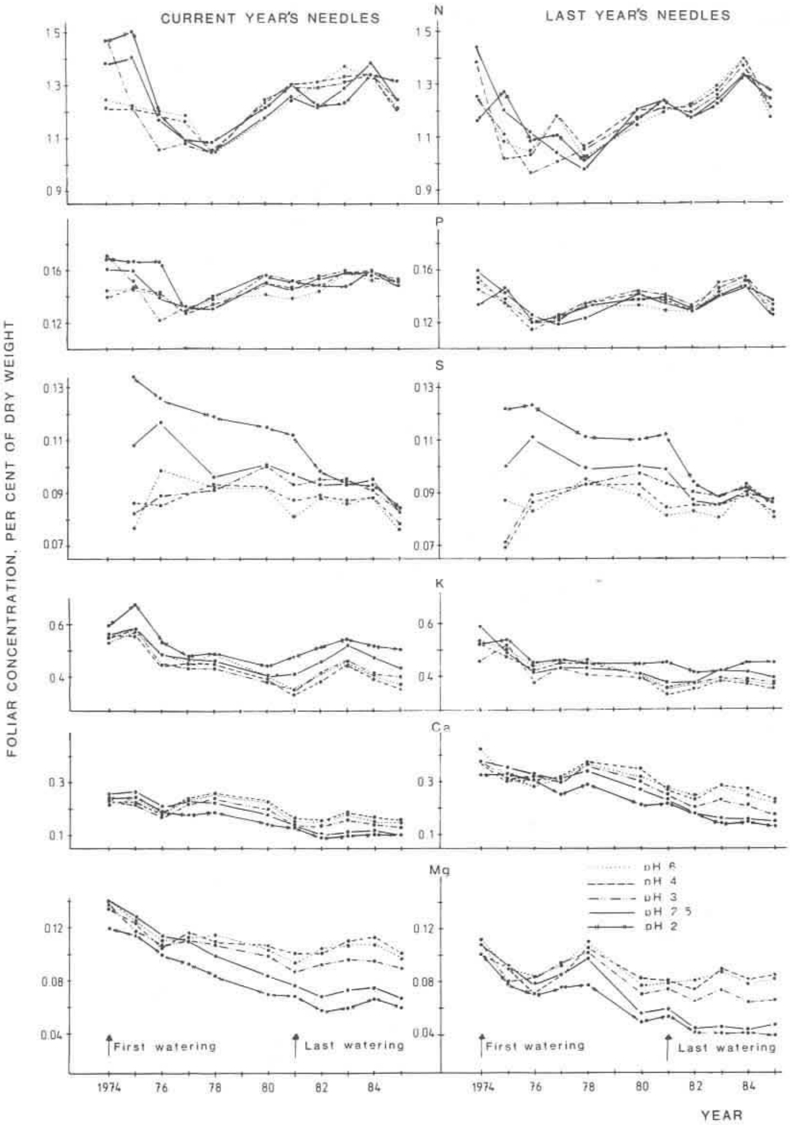

Figure 2. Effects of acid application on the foliar concentrations of macronutrients in Scots pine.

last three-year period, however, base saturation may have increased slightly in the two most acidic treatments. Also in the Bs-horizon the base saturation decreased from 1975 to 1981, but has increased since.

Table 2. ELEMENT CONCENTRATIONS (PER CENT OF DRY WEIGHT) IN CURRENT YEAR'S NEEDLES FOR THE DIFFERENT TREATMENTS IN NOVEMBER 1985.

Element	Treatment					
	m.w.	pH 6	pH 4	pH 3	pH 2.5	pH 2
N	1.20	1.21	1.20	1.24	1.24	1.31
P	0.15	0.15	0.15	0.15	0.15	0.15
K	0.31	0.37	0.35	0.40	0.43	0.50
Ca	0.15	0.15	0.16	0.13	0.10	0.10
Mg	0.102	0.097	0.101	0.090	0.068	0.061
S	0.078	0.076	0.078	0.082	0.083	0.084
SO_4-S	0.004	0.003	0.005	0.005	0.005	0.005
Mn	0.027	0.022	0.022	0.017	0.013	0.011
Zn	0.0042	0.0040	0.0042	0.0037	0.0034	0.0036
Fe	0.0034	0.0031	0.0037	0.0029	0.0032	0.0031
Cu	0.00032	0.00032	0.00031	0.00031	0.00029	0.00030
Al	0.0248	0.0255	0.0257	0.0222	0.0207	0.0218

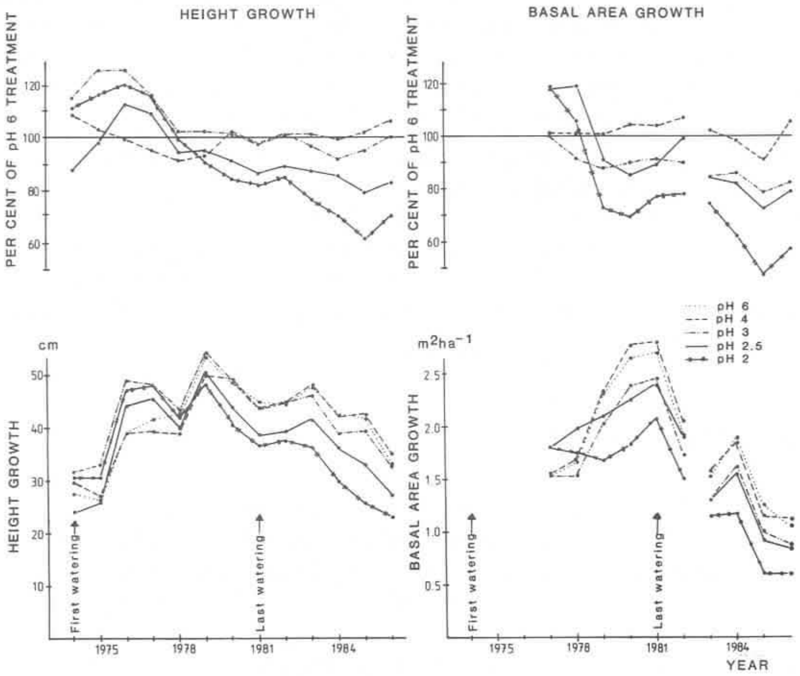

Figure 3. Effects of acid application on the height and basal area growth of Scots pine. The two upper figures show the growth in per cent of the growth on the control plots (pH 6). The two lower figures show the actual growth.

Significant effects of the acid application can be seen for the pH 3, pH 2.5 and pH 2 treatments. The effects are most obvious in the O- and E-horizons.

The foliar concentration of macronutrients is shown for the different years in Figure 2. Table 2 shows the concentration of all essential elements except B in the autumn of 1985. The concentration of Al is also shown. Results for 1986 are not yet available. In order not to overload the figure, results from the unwatered plots are not shown. Of the elements analysed significant effects of the acid application have been found for S, K, Ca, Mg, Mn and Zn. The concentrations of K and S increased with increasing amounts of acid applied, while the other elements decreased. For K and Mg the differences between treatments appear to have increased over time; for S they have decreased. Mg appears to be deficient in the two most acidic treatments. Yellow needles indicating Mg deficiency occur in the lower parts of the crowns. Of the other elements only N is possibly slightly deficient, but the concentration has not been influenced by the treatments. The concentration of Al in the needles has not been significantly influenced by the acid application.

Figure 3 shows the effects on the tree growth. Again, to avoid overloading of the figure results from the unwatered plots are not included. Both the absolute growth and the growth in relation to the control plots (pH 6) are shown. The gap in the basal area growth between 1982 and 1983 is due to a change in the girth measurements. In 1982 and earlier the girth increment was measured 0.5 m above ground, while in subsequent years it was measured at breast height (1.3 m). Clear effects of the acid application can be seen on both height and basal area growth. During the first 4 years the application of acid obviously had a positive effect on tree growth. But since 1978 the growth in the pH 2, pH 2.5 and, partly, pH 3 treatments has decreased compared to the control plots. Relative to the control the height increment in 1985 was 40 per cent lower at the pH 2 treatment and 23 per cent lower at the pH 2.5 treatment. The effect on the basal area growth was even larger. In general there seems to be a negative effect on the tree growth with increasing amounts of acid applied. In 1986 there may be a slight improvement of the growth in all treatments with artificial acid rain.

DISCUSSION AND CONCLUSION

The acid deposition has significantly influenced soil pH and base saturation. This is hardly surprising since the soil studied is very low in material able to neutralize the acid deposited. Since the last glaciation about 10,000 years ago, the pH of this soil has decreased from about 7 to the low values recorded today. This means that the natural production of acid has exceeded the neutralization of acid by silicate weathering and possible other processes. In such soil an extra input of acid has to increase the acidification rate. Significant effects of the acid application have been found for the treatments with pH 3 and below. This means that an extra input of acid of about 20 kmol ha^{-1} has significantly reduced the pH and base saturation of the soil. The treatment corresponds to an acid input equivalent to slightly more than 20 years deposition in southernmost Norway.

The reduction in base saturation of the soil is mainly caused by increased leaching of Ca and Mg. In 1981 the content of exchangeable Ca in the pH 3, pH 2.5 and pH 2 treatments was reduced to 74 per cent, 35 per cent and 11 per cent respectively of the values of the control plots. The corresponding figures for Mg were 52 per cent, 23 per cent and 11 per cent (Abrahamsen, 1984). The content of exchangeable Ca and Mg in the soil is therefore severely reduced in the soil exposed to the highest amounts of acid; this is reflected in the foliage content. Of the elements influenced by the acid application, only Mg appears to be deficient. The reduced growth in the two most acidic treatments and partly in the pH 3 treatment is therefore most likely caused by Mg deficiency. However, Al may be of potential importance. In lysimeter studies, the concentration of total Al in the leachate from soils exposed to artificial rain of pH 2 has been up to 2 mM. In the control lysimeters the highest concentration was 0.1 mM, and in the lysimeters exposed to "rain" of pH 3 the highest concentration was 0.25 mM (Abrahamsen, 1983). There was therefore a dramatic increase in the concentration of total Al when the acidity of the applied water increased from pH 3 to pH 2. There is good reason to assume that the major fraction of this Al is Al^{3+}. This form of Al may be injurious to pine trees. However, studies carried out so far indicate that Scots pine is not very sensitive to Al^{3+}. By means of a sophisticated water culture experiment, Eldhuset (1986) found that the growth of Scots pine was not affected by Al^{3+} until the concentrations exceeded 1 mM in seedlings without mycorrhiza and 3 mM in seedlings with mycorrhiza. Under natural conditions roots are normally infested by mycorhizal fungi. Therefore, the most plausible explanation for the reduced growth still appears to be a reduced Mg supply.

The results obtained in this study are in accordance with results from a similar study on Norway spruce (Stuanes et al., in press). In that study significant growth reduction was found after application of artificial rain of pH 3 and 2.5. Also in that experiment the growth reduction started 5 years after the first application of acid, and continued for 4 years after the application was terminated. In the next 4-year period, from 1983 to 1986, growth improved. The reasons for the growth decline in the Norway spruce experiment are more uncertain. The pH and base saturation of the soil were negatively influenced, as in the present study. However, the reduction in the content of exchangeable Mg in the soil was not as dramatic as in the Scots pine study. Probably for that reason the foliar content of Mg was higher than in the present study. The lowest value observed was 0.07 per cent in the current year's needles and 0.06 per cent in the previous year's needles. These low concentrations lasted for one to three years. It is of course possible that these low Mg concentrations are the main cause of the growth decline. However, on Norway spruce high Al concentrations may be more important. According to a thesis on Al toxicity, Norway spruce starts suffering when the Al^{3+} concentrations exceed 0.4 mM (see Abrahamsen, 1984). In another study it was concluded that Al reduced the growth when the concentrations exceeded 0.3 mM (Eldhuset, 1986). Therefore, according to the results of the lysimeter study previously mentioned (Abrahamsen, 1983), Al might have influenced the growth in the Norway spruce experiment.

Our research project also includes three other similar field experiments (Abrahamsen et al., 1976a). These have in general shown similar effects on the soil as described for the two experiments mentioned above (Abrahamsen, 1980, Stuanes, 1980). However, foliar analyses have not shown any deficiency that can be related to the application of acid (Tveite, 1980a). Nor have the experiments shown any growth reduction that can be related to the treatments (Tveite, 1980b). In one experiment, however, the highest amount of acid applied was relatively small (pH3, 50 mm five times year^{-1}); in another, in a young plantation of spruce, pine and birch, the experimental variation was very large. In the last experiment, in an old Scots pine forest, up to 1000 kg of S have been applied, but no effect on growth has been found so far.

Use of experimental results to evaluate the actual effects of the wet acid deposition must be done with care. Application of dilute sulphuric acid of pH 3 and below over a short period of time has to give other and most likely stronger effects than the natural deposition of more dilute acid. Nevertheless, we think that the results indicate that on sensitive soils the long term effect of the wet acid deposition will be a slow increase in soil acidity and a gradual decline in the supply of Ca, Mg, Mn and Zn. The results indicate that the supply of Mg may be of special concern (Abrahamsen et al., 1976a, Abrahamsen, 1980). The deficiency in Mg is likely to be intensified by the deposition of N from the atmosphere (Abrahamsen, 1980). This deposition will most likely increase the forest growth and thereby increase the requirement for Mg and other plant nutrients. Deficiency in Mg is quite widespread in forests in Germany (e.g. Rehfuess, 1983, Zoettl and Huettle, 1986). This deficiency is believed to be caused mainly by a combination of ozone injury and increased foliar leaching of Mg (e.g. Rehfuess, 1983). However, according to Zoettl and Huettle (1986), symptoms of Mg deficiency appear to be most common on soils low in Mg. The possibility can therefore hardly be ruled out that at least part of the Mg deficiency is caused by a reduced supply of Mg in the soil due to acid deposition.

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